*On the Absorption of X-Rays in Copper and Aluminium.**

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Much experimental work has been directed towards the determination of the absorption coefficients of X-rays in elements—especially with respect to the relation existing between the absorption coefficient and the wave-length—owing to the importance of the bearing of the results on the theories of electromagnetic radiation and atomic structure. Nevertheless, on account of the experimental difficulties encountered in this work, serious discrepancies appear among the results of different observers. The method described below appears to offer a reliable and accurate means of measuring the absorption coefficients of homogeneous X-rays in various materials and the wave-lengths of the rays employed.

Among the difficulties experienced in the experimental arrangements, two of the chief are:—

(*a*) The heterogeneity of the source.

(*b*) The variations in intensity of the source.

By making use of the reflection of X-rays by crystals, it is possible to analyse a beam of X-rays into its component wave-lengths. According to the classical equation of Bragg, we have, if d = spacing of the crystal grating; θ = glancing angle of the incident ray; λ = wave-length of the reflected ray; n = order of the spectrum;

then $$2 \,.\, d \,.\, \sin\theta = n\lambda.$$

It is to be observed that the reflected ray may contain, in addition to the primary wave corresponding to $n = 1$, other waves of lengths $\lambda/2$, $\lambda/3$, etc., *i.e.*, submultiples of the primary wave-length λ, corresponding to $n = 2, 3$, etc., respectively.

In these experiments the interference method of obtaining homogeneous beams was employed, a rock-salt crystal being used to analyse a beam of X-rays generated by a Coolidge tube. The difficulty introduced by the possibility of the reflected beam being mixed with waves of a higher order than the first was obviated in the following way. It has been shown by Duane and Hunt† that the voltage V, required to excite a wave of frequency n is given by the equation $eV = nh$ (e = electronic charge;

* An account of research work carried out in the Memorial Physical Research Laboratory of the University College of South Wales and Monmouthshire, Cardiff.

† 'Phys. Rev.,' vol. 6, No. 2, p. 169.

h = Planck's constant). Thus by carefully adjusting the voltage applied to the tube, keeping it so as to be—for any particular setting of the crystal—just below that required to produce the reflected wave of the second order, homogeneous rays were obtained. This principle is illustrated in fig. 1, which shows the change in the log-absorption curve for aluminium

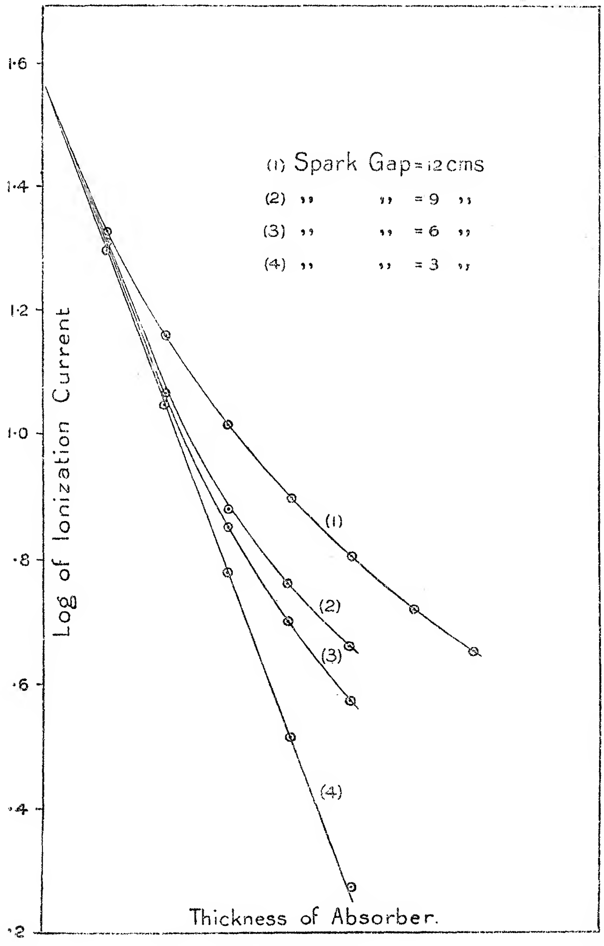

FIG. 1.

with the variation in the voltage applied to the tube, as measured by the alternative spark-gap between two bright metal spheres 1 cm. in diameter; the wave-length of the X-ray was approximately 0·58 Å.U. The log-absorption curve becomes a straight line (4) when the waves of higher order than the first are eliminated by a sufficient reduction of the voltage.

In order to correct for the variations in intensity, which were pronounced,

a special device was used. Instead of employing an ionisation chamber of the ordinary pattern, a double one was constructed.

This consisted of a rectangular metal case AB (fig. 2), divided longitudinally into two by the metal plate CD. Through the upper and lower compartments of this ionisation chamber were passed respectively the insulated

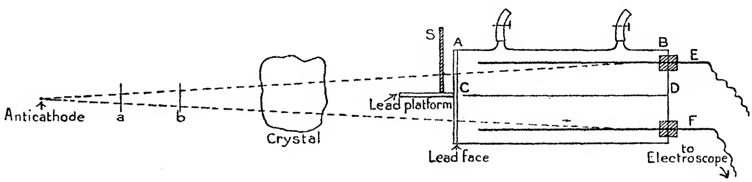

Fig. 2.

electrodes E and F, which could be placed separately in connection with an electroscope. The beam of X-rays reflected from the crystal was thus split into two parts; and the ionisation produced by that entering the lower compartment provided the data to correct for the variations in the beam proceeding into the upper one.

Thus in making a determination of the absorption coefficient of a substance, the electrodes E and F were first connected to earth and afterwards insulated. The X-ray bulb was then excited for a certain period, at the expiration of which E and F were connected in turn to the electroscope, and the ionisation produced in each chamber measured. Several sheets of the absorbers were placed before the upper slit in succession, and the above process repeated in each case. After making the necessary corrections and reducing all the readings of the upper chamber to a standard reading of the lower, a curve was plotted showing the relation between the log of the ionisation current and the thickness of the absorber. Very consistent results were obtained in this way, the points all lying very evenly on a straight line—indeed, the results for the absorption coefficient obtained in independent experiments rarely varied by more than 1 per cent., or very occasionally by 2 per cent.

As an illustration of the method of working, the actual readings taken in an experiment are given below in Table I; while fig. 3 is the log-absorption curve obtained from these readings, and is typical of the curves given by this method. The results obtained are summarised below in Table II; the wave-lengths were standardised by observing the position of reflection of the β peak of the platinum spectrum.

These results present some interesting features. It is well known, for example, that the ratio of the absorption coefficient of one substance to that of another is approximately independent of the wave-length, provided the

Table I.

Reading of spectrometer table. θ.	No. of sheets of absorber.	Actual readings taken of		Readings corrected for calibration.		Readings corrected for charging up.		Reduction of readings of E to F = 20.	Mean.	Calibration of electroscope.		
		E.	F.	E.	F.	E.	F.			Deflection.	Volts.	
93° 30′ ($\lambda = 0 \cdot 480$ A.U.)		27 ·0	12 ·0	24 ·5	12 ·0	23 ·3	11 ·4	40 ·8		0	0	Mass of aluminium per unit of area $= 0 \cdot 08412$ grm.
		41 ·0	17 ·0	33 ·0	16 ·5	31 ·4	15 ·7	40		8 ·0	0 ·2	
		42 ·0	18 ·0	34 ·0	17 ·0	32 ·3	16 ·2	40		16 ·5	0 ·4	
	0	26 ·5	12 ·0	24 ·0	12 ·0	22 ·8	11 ·4	41 ·7	40 ·4	26 ·5	0 ·6	
		31 ·0	13 ·0	27 ·0	13 ·0	25 ·7	12 ·3	40 ·3		39 ·0	0 ·8	
		30 ·5	13 ·0	26 ·5	13 ·0	24 ·8	12 ·3	40		45 ·0	1 ·0	
		33 ·0	14 ·5	28 ·0	14 ·0	26 ·6	13 ·3	40				
		29 ·5	12 ·5	25 ·5	12 ·5	24 ·3	12 ·0	40 ·4				
		37 ·0	19 ·0	31 ·0	18 ·0	29 ·2	17 ·4	33 ·5				
		41 ·0	21 ·0	34 ·0	19 ·5	32 ·1	18 ·6	34 ·5				
		39 ·0	20 ·0	32 ·0	18 ·5	30 ·2	17 ·7	34 ·1				
	1	21 ·0	11 ·5	19 ·5	11 ·5	18 ·4	10 ·9	34 ·0	34 ·0			
		29 ·5	15 ·5	25 ·5	15 ·0	24 ·0	14 ·3	33 ·6				
		21 ·5	11 ·5	20 ·0	11 ·5	18 ·8	10 ·9	34 ·5				
		25 ·5	16 ·5	23 ·0	16 ·0	21 ·4	15 ·2	28 ·1				
		36 ·0	21 ·5	30 ·0	20 ·0	28 ·0	19 ·0	29 ·4				
	2	25 ·0	16 ·0	23 ·0	15 ·5	21 ·5	14 ·8	29 ·0	28 ·6			
		26 ·0	16 ·5	23 ·5	16 ·0	21 ·9	15 ·2	29 ·0				
		21 ·0	14 ·0	19 ·5	13 ·8	18 ·1	13 ·1	28 ·0				
		14 ·0	11 ·0	13 ·8	11	12 ·7	10 ·5	24 ·2				
		19 ·5	15 ·5	18 ·5	15	17 ·0	14 ·3	23 ·7				
	3	17 ·5	14 ·0	16 ·5	13 ·8	15 ·1	13 ·1	23 ·5	23 ·9			
		21 ·5	17 ·0	20 ·0	16 ·0	18 ·4	15 ·2	24 ·2				
		24 ·5	19 ·0	22 ·5	18	20 ·7	17 ·1	24 ·2				
		15 ·0	14 ·0	14 ·7	13 ·8	13 ·3	13 ·1	20 ·3				
		14 ·0	12 ·8	13 ·8	12 ·8	12 ·5	12 ·2	20 ·4				
	4	16 ·0	15 ·0	15 ·5	14 ·7	14 ·0	14 ·0	20 ·0	20 ·1			
		17 ·0	16 ·0	16 ·4	15 ·6	14 ·8	14 ·8	20 ·0				
		17 ·0	16 ·0	16 ·4	15 ·6	14 ·8	14 ·8	20 ·0				
	Lead 2 mm. thick.	2 ·0	23									
		2 ·0	24									
		2 ·0	23									
	Both E and F screened with lead.	2	1									
		2	1									
		2	1									

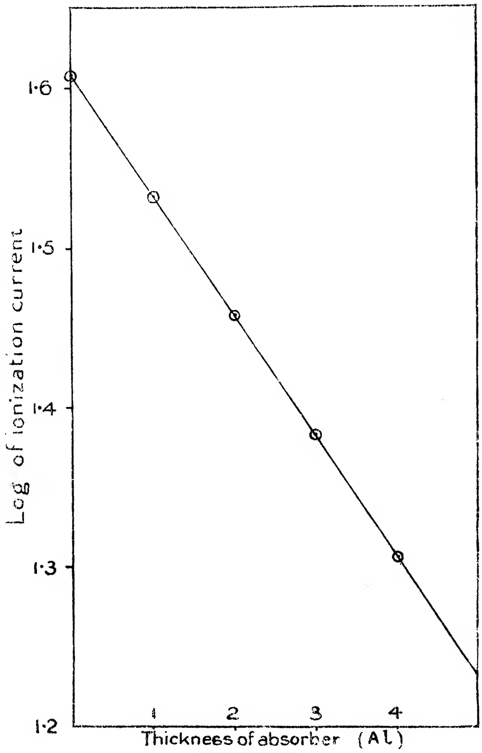

FIG. 3.

Table II.

Wave-length × 10^{-8}.	μ/ρ.	
	Aluminium.	Copper.
0·431	1·483	14·32
0·456	1·654	16·67
0·480	2·036	20·65
0·504	2·050	23·00
0·529	2·600	26·63
0·553	2·748	29·57
0·577	3·102	32·70
0·627	4·039	41·17

wave-lengths do not include any near those characteristic of the absorber. If now we plot μ/ρ_{Al} against μ/ρ_{Cu} in a graph, we get the curve shown in fig. 4. A striking feature about this curve is that a break appears in it at a wave-length $\lambda = 0·49$ Å.U. (mass absorption coefficient, 2); it is significant that Barkla* obtained evidence of the emission by aluminium of a J radiation,

* See "Bakerian Lecture," 1916, 'Phil. Trans.,' A, vol. 217, p. 352.

the wave-length of which was approximately equal to this (mass absorption coefficient, 1·9). The results obtained by Pierce, who has also measured

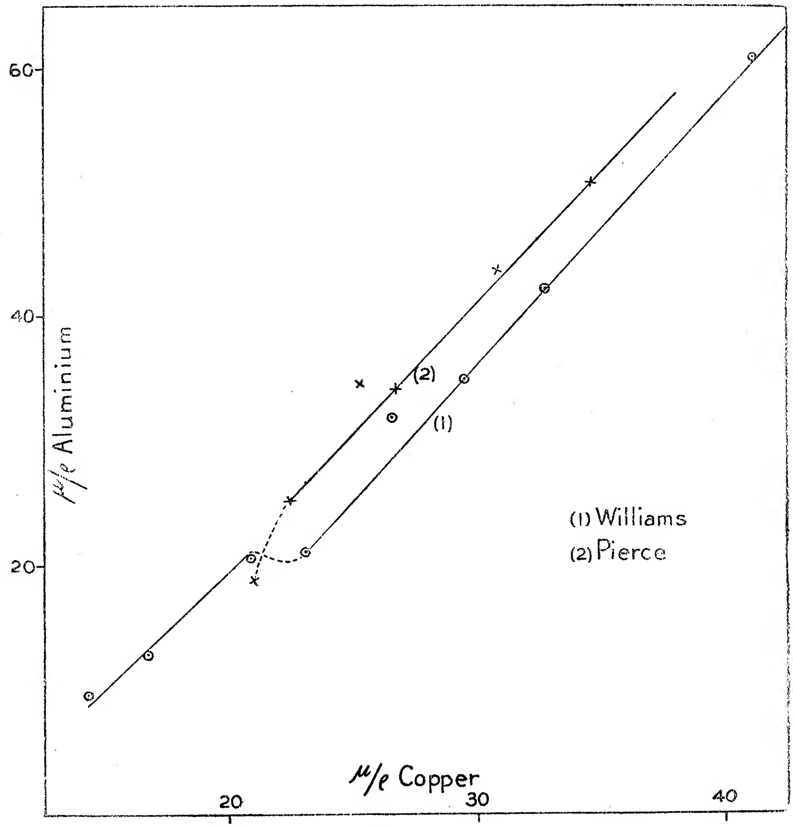

FIG. 4.

absorption coefficients over this range, are also shown in fig. 4. The slope of the line representing Pierce's results agrees with that found in these experiments; while there is also evidence of a discontinuity at $\lambda = 0{\cdot}49^{-10}$ cm. Unfortunately, Pierce did not extend his observations far enough in the direction of the shorter waves to establish this with certainty.

Barkla,* from his most recent results, considers that the wave-length of the characteristic J radiation of aluminium is about 0·37 Å.U. It is to be noticed, however, as he himself points out, that the radiations used in his absorption experiments were not homogeneous, and hence the wave-length as deduced from the mass absorption coefficient in aluminium is subject to error: *e.g.*, Bragg found that the silver characteristic rays consisted of two waves of wave-length 0·491 and 0·554 Å.U., and with absorption coefficients

* 'Phil. Mag.,' October, 1917, p. 273.

1·94 and 2·7 respectively, while the absorption coefficient given by Barkla was 2·5—a mean between these two numbers.

Previous results have indicated that the relation between the absorption coefficient and the wave-length may be expressed, at least approximately, by the formula $\mu/\rho = a \,.\, \lambda^n + C$, where a, n and C are constants, C representing the scattering coefficient. The value $n = 3$ appears to be the most satisfactory for the results obtained hitherto.

The following curves (fig. 5) were obtained by plotting μ/ρ against λ^3.

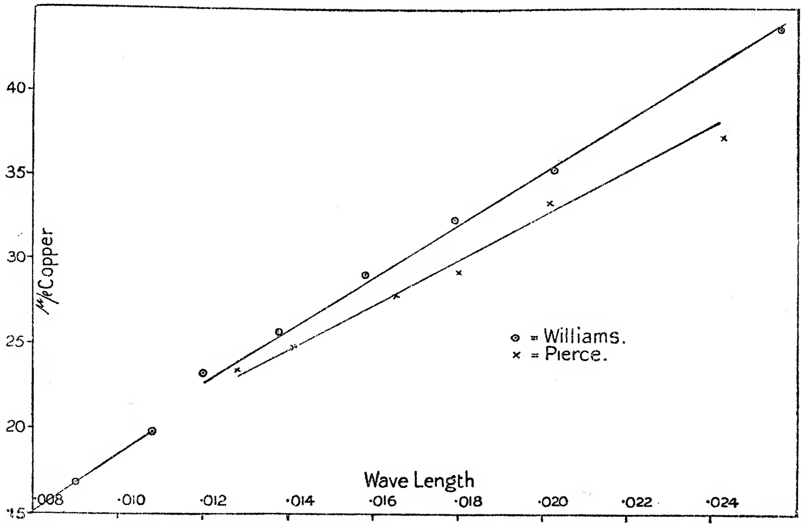

Fig. 5a. Wave Length should read (Wave Length)^3.

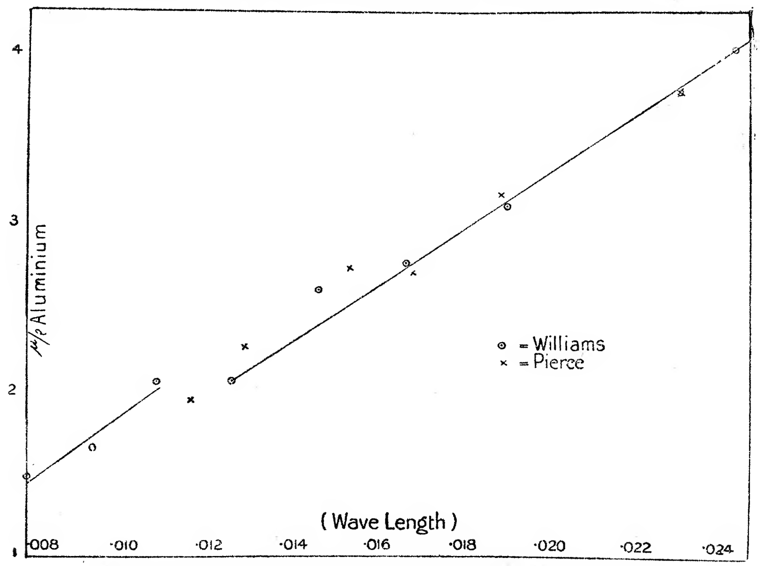

Fig. 5b. (Wave Length) should read (Wave Length)^3.

It will be seen that the points lie approximately on a straight line, though, here again, the break in the aluminium curve at a wave-length $\lambda = 0{\cdot}49$ Å.U. is pronounced, while there is also evidence of a discontinuity in the copper curve at a wave-length a little below that at which the break occurs in the aluminium curve—a result similar to that obtained by Barkla.

Fig. 6 shows the curves by plotting log μ/ρ against log λ for aluminium and copper respectively. In the two cases the graphs are straight lines; but while the slope for the aluminium line is 3, that for copper—in which case the points are particularly regular—is almost exactly 5/2—a result in agreement with Owen's 5th power absorption law. These curves also bring out very clearly the fact that discontinuities occur both in the case of copper and of aluminium at wave-lengths 0·448 and 0·49 respectively.

Thus it appears that the value of n which best satisfies the results beyond a discontinuity is 3 in the case of aluminium, and 5/2 in that of copper. It should be remembered, however, that the scattering coefficient C has been neglected. We should, therefore, more accurately have plotted log $(\mu/\rho - C)$ against log λ. The values given for C range from 0·1 to 0·2; and it will be found that the slope in the case either of copper or of aluminium is not materially affected by the inclusion of the scattering coefficient.

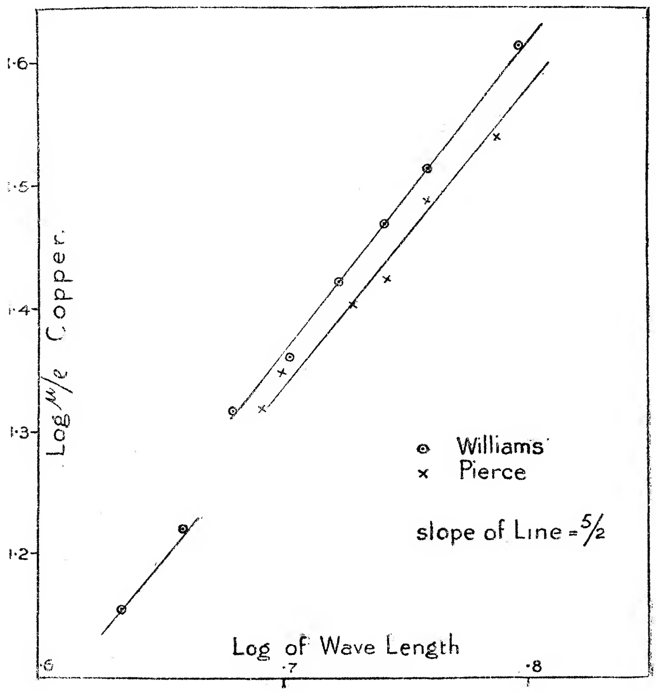

FIG. 6A.

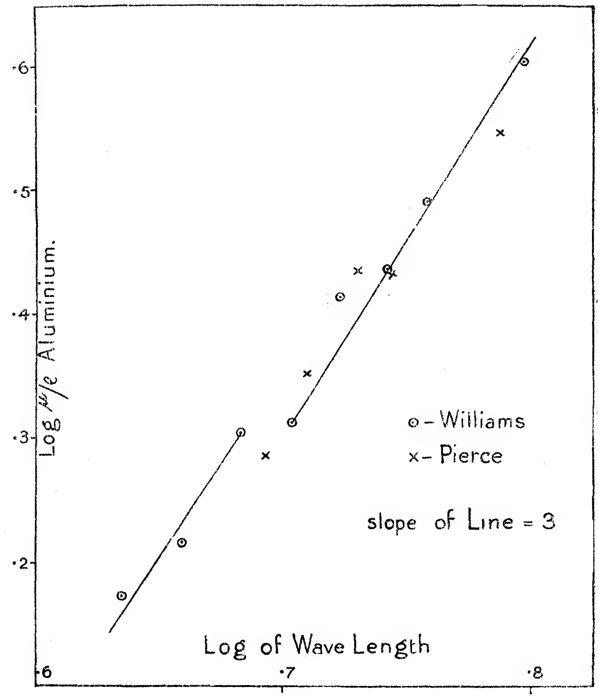

FIG. 6B.

I desire to express my thanks to Principal Griffiths for the interest he has shown in the work, and for his kind consideration in regard to my wants. I am also indebted to Captain J. H. Shaxby for much valuable advice and criticism. Part of the expenses incurred in the research has been defrayed by a special grant from the University of Wales.